

# Design, simulation, fabrication and characterization of novel single use MEMS resistor controllers

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**Abstract** Two novel types of single use MEMS resistor controllers are described and the performance test results are presented. The increment controller mechanically breaks metallic lines and the decrement controller connects a group of electrodes, therefore, the single use controlling can be realized. Controlling is accomplished by a voltage pulse supplied by an energy storage capacitor through a metal bridge igniter. Key features of the controllers include bistability, integratability and IC compatibility. The controllers can be driven by external signal with long predicted lifetime, therefore, both controllers can be used in systems for long-term storage. And, planar processing method is used for batch fabrication.

## 1 Introduction

The presented resistor controllers can adjust the electrical current in the circuit or the voltage distribution. To realize the resistor controlling, there are tremendous kinds of potentiometers in the electrical apparatuses (Liu et al. 2013), most of which have relatively large volume, and configure the resistance value by setting contact points accessed by the sliding-mode terminal or other kind of force to alter the resistance value (Cid-Pastor et al. 2013; Paul et al. 2012). But with the fragile and rough mechanism of assembled, discrete and moving parts, under the highly dynamic environment, the driving and the maintenance can be unstable, and the performance can be defective in

the instant circuit configuration caused by instantaneous events, not only temporary, but also can be permanent (Woo et al. 2013). The switching time response can not fulfill the requirement in the high speed application, either.

The introduced single use MEMS resistor controllers use storage capacitor as power supply, and a current pulse ignites the metal bridge to set the required resistance value by shaping the resistor unit. The action will be triggered by the electronic signal rather than external mechanical forcing, which optimizes the package geometrical design and minimizes the volume of the unit. And with no mechanical moving parts, the design principle integrating control and resistor unit has valuable advantages in high dynamic or other extreme environment for reliability reasons, therefore, it is useful in the increasing design compromises in size and mechanics. And due to the fabrication process, the MEMS resistor controllers satisfy the highly integrated, reliable and IC compatible requirements.

## 2 Theory of MEMS metal bridge igniter

MEMS metal bridge igniter is a new type of micro-igniter with advantages of low power consumption and small size. MEMS metal bridge igniter design is based on electrical explosion theory.

With the law of conservation of energy, the mathematical model of perfect explosion of metal bridge under the storage capacitor discharge excitation is established, taking into account the rule of resistivity changes, the rule specifies heat capacity changes and the influence of phase transition. The specific relationship between whether there is a perfect explosion of metal bridge or not between bridge parameters, external energy and power input is obtained.

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## 2.1 The Joule heating model of the bridge within single phase

The temperature of the bridge area rises with the internal current excitation as the heat source. Combining the heat induced at the bridge area, the capacitor discharging equation can yield the formula:

$$Q = \int_{t_0}^{t_M} \left( i_{t_0} e^{-\frac{t}{R_{bs}C}} \right)^2 R_{bs} dt \quad (1)$$

$R_{bs}$  is the equivalent value of the bridge area resistor, and  $t_M$  is the melting time of the metal bridge.

The Joule heating equation of the bridge area is given by

$$\int_{t_0}^{t_M} \left( i_{t_0} e^{-\frac{t}{R_{bs}C}} \right)^2 R_{bs} dt = \int_{T_0}^{T_M} c_{bs} m_{bs} dT \quad (2)$$

## 2.2 Elevating temperature model of the first phase transition

During phase transition analysis, it may be more convenient to work in terms of a limited area, the Joule heating equation is

$$\int_{t_{M1}}^{t_L} \left( i_{t_{M1}} e^{-\frac{t-t_{M1}}{R_{bsl}C}} \right)^2 R_{bsl} dt = m_{bs} \frac{T - T_{M1}}{T_{L1} - T_{M1}} L_1 \quad (3)$$

For the ultimate explosion of the metal bridge, the energy storage requirement of capacitor can be expressed as

$$\left\{ \begin{array}{l} Q > \int_{T_0}^{T_{M1}} c_{bs} m_{bs} dT + \int_{T_{L1}}^{T_{V1}} c_{bl} m_b dT + m_{bs} L_1 + m_{bs} L_2 \\ Q = \frac{1}{2} CV^2 \end{array} \right. \quad (4)$$

The required minimal energy for explosion can be calculated for the bridge area with given dimensions and materials. Therefore, the minimal burst time under different capacitances and voltages can be specified, respectively.

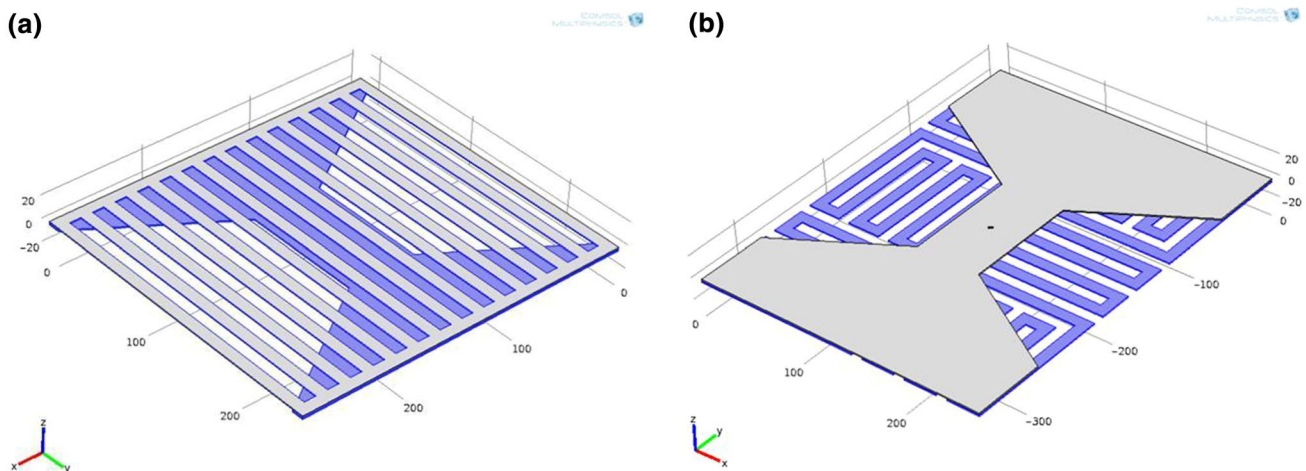
In order to ignite the bridge area, the absorbed energy of the bridge should meet the condition described as below:

$$\begin{aligned} & \int_{t_0}^{t_{M1}} \left( i_{t_0} e^{-\frac{t}{R_{bs}C}} \right)^2 R_{bs} dt + \int_{t_{M1}}^{t_{L1}} \left( i_{t_{M1}} e^{-\frac{t-t_{M1}}{R_{bsl}C}} \right)^2 R_{bsl} dt \\ & + \int_{t_{L1}}^{t_{V1}} \left( i_{t_{L1}} e^{-\frac{t-t_{L1}}{R_{bl}C}} \right)^2 R_{bl} dt \\ & + \int_{t_{V1}}^{t_{G1}} \left( i_{t_{V1}} e^{-\frac{t-t_{V1}}{R_{blg}C}} \right)^2 R_{blg} dt > \int_{T_0}^{T_{M1}} c_{bs} m_{bs} dT \\ & + \int_{T_{L1}}^{T_{V1}} c_{bl} m_b dT + m_{bs} L_1 + m_{bs} L_2 \end{aligned} \quad (5)$$

In which, the bridge resistor varies as in different phases from the liquid state to gas state.

## 3 The resistor controller design with MEMS metal bridge igniter

MEMS metal bridge igniter is a new type of micro-igniter with advantages of low power consumption and small size, and is designed based on electrical explosion theory. With the perfect explosion of metal bridge under the storage capacitor discharge excitation, the typical metal bridge igniter can be used as solid state switches.



**Fig. 1** Resistor controller designs. **a** The increment controller. **b** The decrement controller

The MEMS metal bridge igniter in this form can even be integrated directly with the resistor unit, expanding the switch application to the resistor controller. The two kinds of resistor controllers simulation models are shown in Fig. 1.

The metal bridges change the shape of the resistor structure by explosion damage in order to change the resistance value. There are two major layers in the resistor controller. In the increment controller, the resistor layer is above the metal bridge layer, and in the decrement controller, just the other way, the resistor layer is beneath the metal bridge layer.

In the increment controller, the initial paralleled metal resistance of the increment controller can be expressed as:

$$R = \frac{R_0}{N} \quad (6)$$

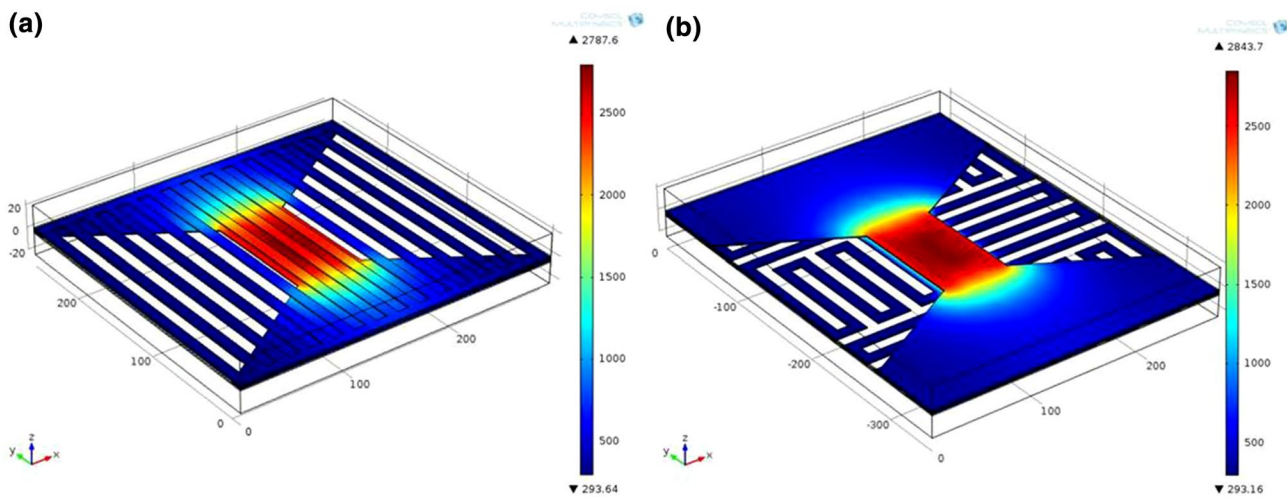
where  $R_0$  is the single stripe resistance,  $N$  is the stripe number.

The metal bridge is deposited under the resistor, and is ignited by the external energy. Therefore, the resistor stripes within the area are damaged, and the account can be calculated as:

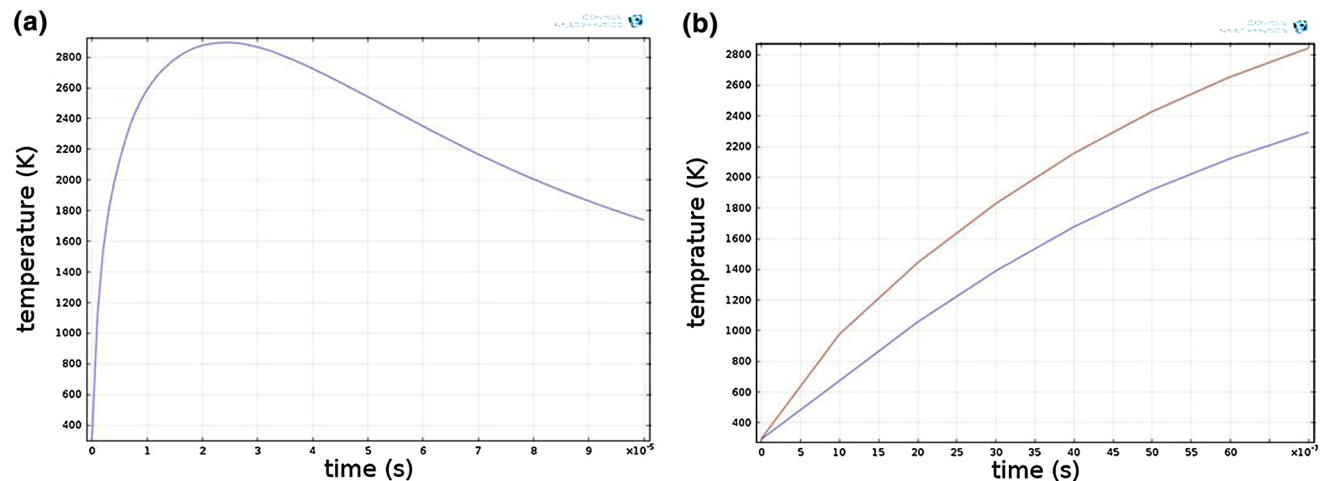
$$N_1 = \left\lceil \frac{w}{d} \right\rceil \quad (7)$$

$$d = d_1 + d_2 \quad (8)$$

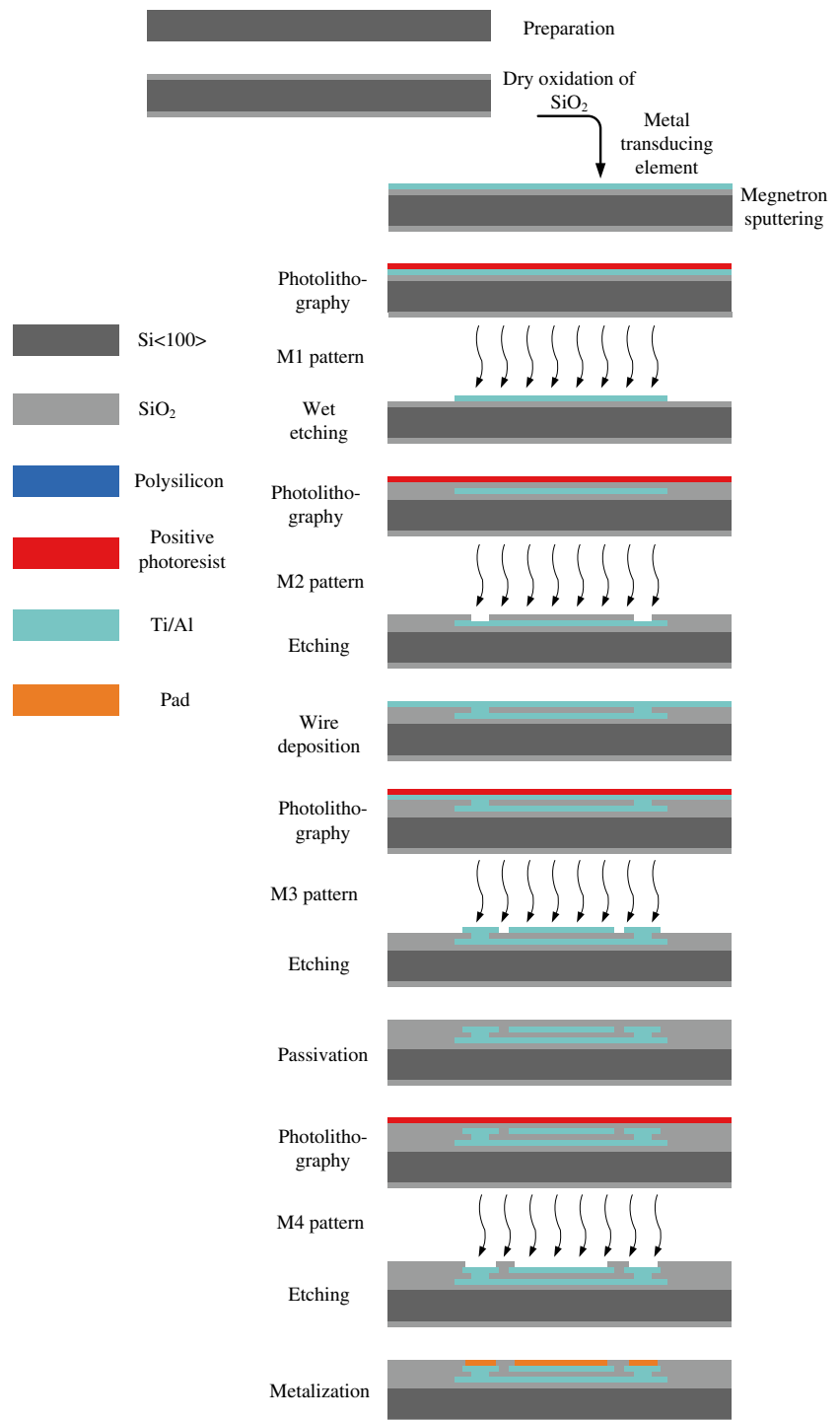
$w$  is the metal bridge width,  $d_1$  is the resistor stripe width,  $d_2$  is the space between two resistor strips. The remaining stripe number is  $N - N_1$ , and the resistance value after the ignition can be given as:



**Fig. 2** Temperature distribution. **a** Increment controller. **b** Decrement controller



**Fig. 3** The time–temperature characteristics. **a** Increment controller. **b** Decrement controller

**Fig. 4** Illustration of steps in processes

$$R = \frac{R_0}{N - N_1} \quad (9)$$

As the counterpart, the decrement controller consists of the metal bridge layer and the meander resistor layer. With the given resistor material, the sheet resistance approximate of a sheet resistor with fixed thickness can be written as:

$\rho$  is the resistivity of the meander resistor,  $t_x$  is the thickness. The resistance of the meander resistor can be described as:

$$R = R_n \frac{l}{w} \quad (11)$$

The metal bridge is on the top of the resistor, and the fragments and residue of it will cover part of the meander resistor, with the coverage area related to the metal bridge area. Accordingly, the larger area is obtained after the explosion, the smaller the resistor becomes. The resistance values before and after the explosion are therefore key design parameters.

#### 4 The simulation and analysis of resistor controller

In this section, the finite element models (FEM) of the resistor controllers are presented by COMSOL (Ongkodjojo et al. 2008). During the transient analysis with joule heating module of COMSOL, the temperature distributions simulations of the increment and decrement controllers with Al bridge are shown in Fig. 2.

Figure 3 illustrates the different time–temperature characteristics of the increment and decrement controllers,

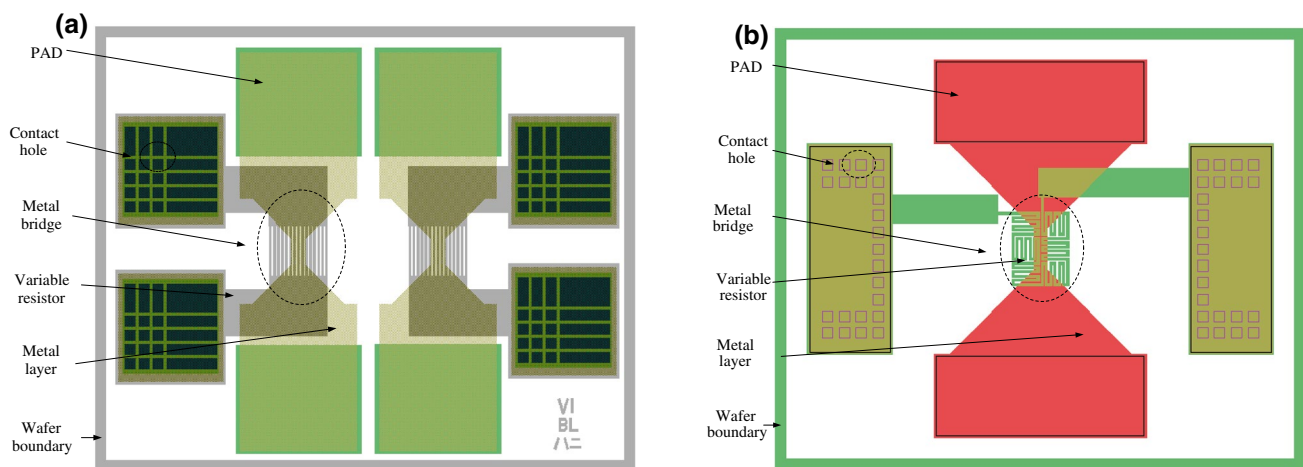
indicating there is an temperature maximum at the bridge area of 2,983 K satisfying the explosion, larger than the melting point of Al, with the power capacitor discharging. Hence, the resistance value can be changed as expected (Fig. 4).

#### 5 Fabrication of resistor controllers

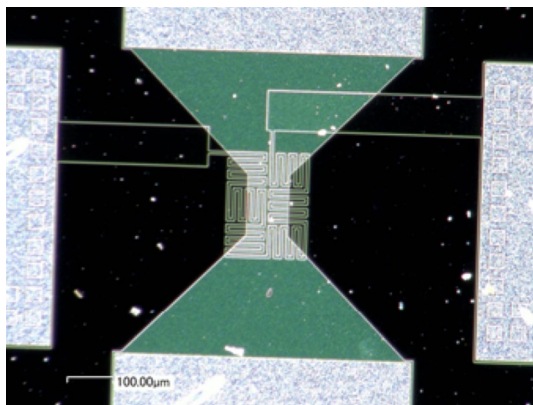
The fabrication process of resistor controller can be explained, taking the increment controller for example as below:

##### 5.1 Layout processing of the increment controller

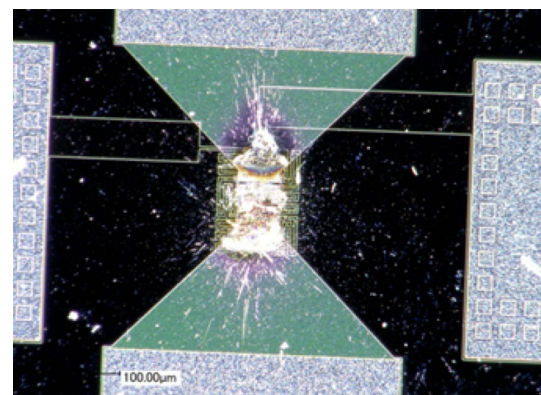
Firstly, prepare the P<100> substrate on a silicon wafer with thickness of 350  $\mu\text{m}$ , followed by the step of washing, and the dry oxidation under 1,050  $^{\circ}\text{C}$  to grow the  $\text{SiO}_2$  isolation. And then based on the different materials for the



**Fig. 5** Layout designs. **a** The increment controller. **b** The decrement controller



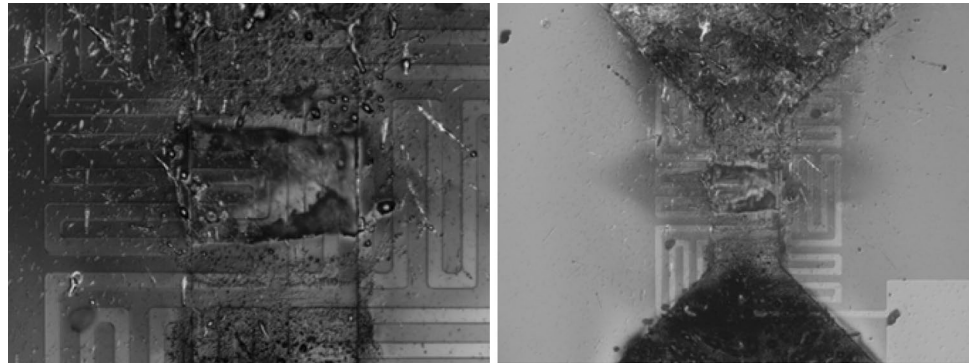
**Fig. 6** Photo of the decrement controller



**Fig. 7** Decrement controller after explosion



**Fig. 8** Microscope images of decrement controller after explosion



**Table 1** Test results of decrement controllers

Bridge size ( $\mu\text{m}$ )	Initial resistance ( $\text{k}\Omega$ )	After resistance ( $\text{k}\Omega$ )	Conditions	Results
$100 \times 200$	3.14	0.614	50 V, discharging capacitance of $47 \mu\text{F}$	Expected action
$150 \times 200$	2.84	0.342	50 V, Discharging capacitance of $47 \mu\text{F}$	Expected action

transducing element, deposit polysilicon and metal bridge of  $40 \times 20 \times 1 \mu\text{m}$  by low pressure chemical vapor deposition (LPCVD). After the first-time exposure, patterned using photolithography, wafer etching is done to obtain the shape of the transducing element with thickness of  $1 \mu\text{m}$ , the second layer of  $\text{SiO}_2$  isolation with thickness of  $1 \mu\text{m}$  is deposited by plasma enhanced chemical vapor deposition (PECVD) to isolate the bridge and wire, and hence with the tolerances satisfaction verified by experiment results.

To obtain acceptable electric characteristic and more effective area, the metal wire thickness of the bridge is larger than that of integrated circuits.

## 5.2 Fabrication of the two resistor controllers

The layouts of the prototype resistor controllers are shown in Fig. 5. The resistance layer is connected to the applying circuit, and the metal bridge layer is controlled by the storage capacitor. Batch fabrication using planar processing methods is used, therefore, it is compatible with the IC process, which is crucial for the usage demanding resistor multiple times of increase or decrease.

## 6 Tests of resistor controllers

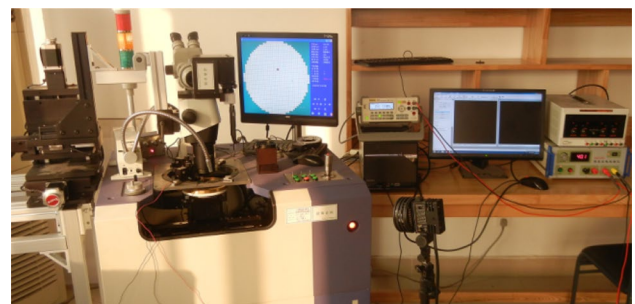
The experiments mainly include the decrement controller, as it can represent the major electrical characteristics of the resistor controllers. And the photo of the decrement controller before the explosion is shown in Fig. 6. The explosion occurs at the metal bridge area, and the fragments and the residue of the metal bridge increase the practical conducting of the resistor, by filling and covering the fine

slots of the meander resistor. Although the metal bridge is ignited to be exploded, the resistor layer beneath is expected remain the original (Fig. 7).

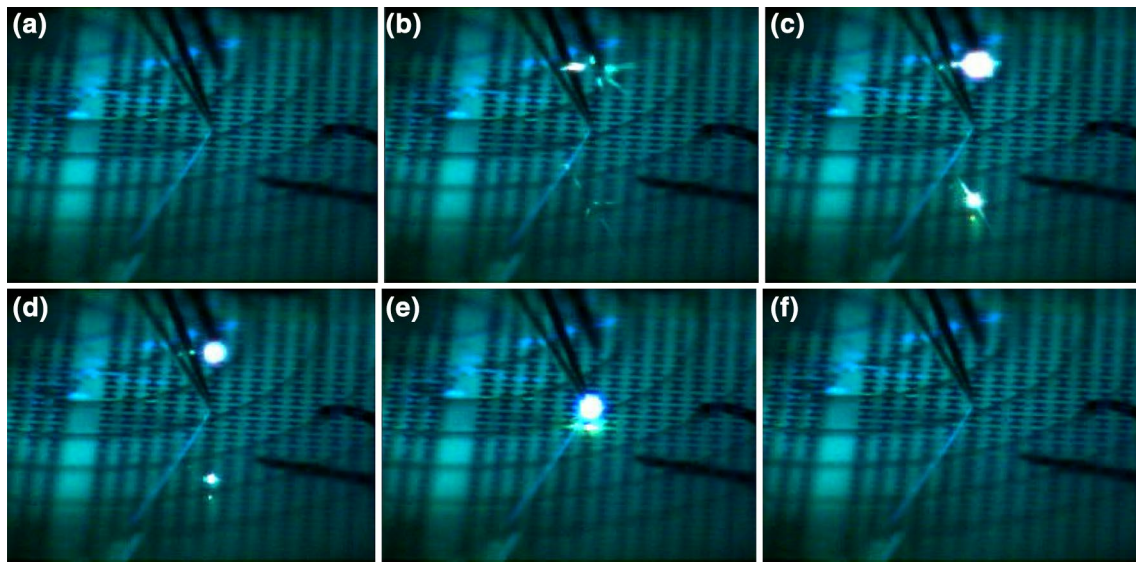
From the microscope images of the metal bridge area after the explosion in Fig. 8, it can be deduced that the resistor stays the intact conditions and the activity area concentrates on the metal bridge. As a result, the transition of the resistance value is determined by the explosion effects on the targeted area.

Base on the issues mentioned above, it can be concluded that, the reliable resistor switching requires electrical explosion on metal bridge. Therefore, aluminum meets the expected requirements of the material. The experiment results are reported in Table 1, which shows the resistance change as predicted.

From the microscope images and the test results, it can be deduced that the large amount of sputter of the metal bridge after the explosion cover the surface of the meander resistor to form the short circuit. The resistance values shrink to the 1/10–1/5 of the initial, which is the discrete



**Fig. 9** Photograph of the wafer-level high dynamic testing system



**Fig. 10** Spark shapes recorded by the high-speed camera. **a** Before the ignition. **b** Electric arc establishment. **c** Arc growth I. **d** Arc growth II. **e** End of arc. **f** After the ignition

values, instead of the linear change. Also, the effective mass of the metal bridge is the key factor of the results, the larger metal bridge is, the larger splitting pieces spread (Figs. 9, 10).

Therefore, the resistor controller can meet the design requirements, which is valuable in the application where the environment conditions should be compared with a reference value.

## 7 Conclusions

The specific design, simulation and fabrication process of single use MEMS resistor controllers based on metal bridge igniter have been presented. The practical working principle achieves key features of the switches include discrete resistor transition, integratability and IC compatibility. The controllers can be driven by external signal with long predicted lifetime, therefore, the resistor controllers can be used in systems for long-term storage. Planar processing method is used for batch fabrication.

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